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DIRECT EMBEDMENT VIBRATORY ANCHOR

NAVAL CIVIL ENGINEERING LABORATORY

JUNE 1973

Technical Report

R 791

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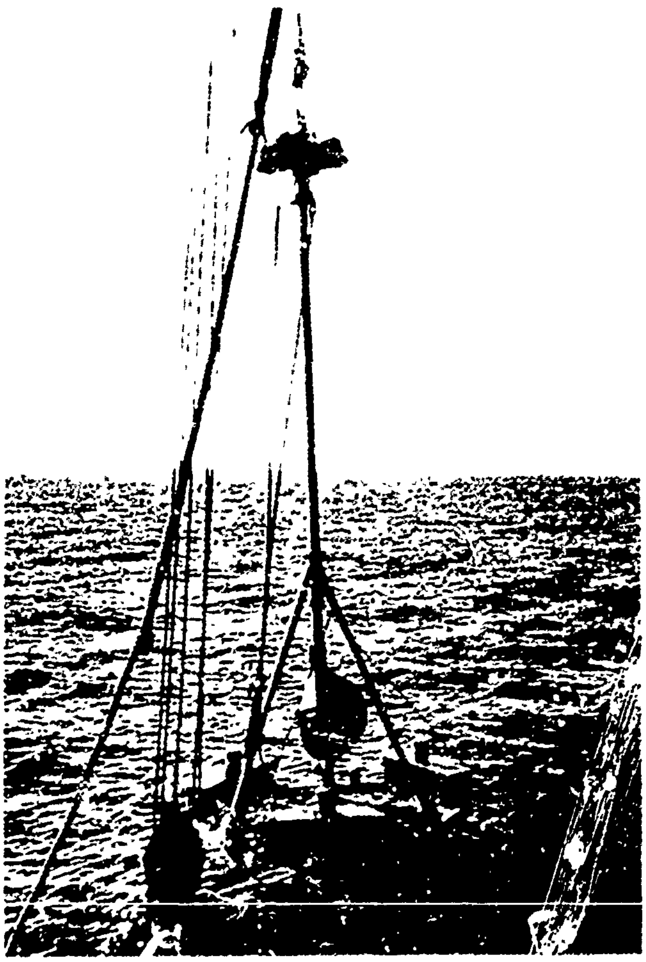
June 1973

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043



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By

R. M. Beard

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Copies available at the National Technical Information Service (NTIS), Sills Building, 5285 Port Royal Road, Springfield, Va 22151

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Civil Engineering Laboratory Port Hueneme, California 93043	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE DIRECT EMBEDMENT VIBRATORY ANCHOR	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final; March 1968 – July 1972	
5. AUTHOR(S) (First name, middle initial, last name) R. M. Beard	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1973	~~28~~ 32	11

8a. CONTRACT OR GRANT NO. b. PROJECT NO. 3.1330-1 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TR-791 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Facilities Engineering Command Washington, D.C. 20390

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Unclassified

Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Deep ocean mooring						
Embedment anchors						
Vibratory anchors						
Seafloor soils						
Short-term holding capacity						
Prototype anchor						
Anchoring efficiency						
Fluke-shaft assembly						
Vibrator						
Support-guidance frame						
Battery power pack						

DD FORM 1473 (BACK)
(PAGE 2)

Unclassified
Security Classification

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INTRODUCTION

Up until recently, the ocean engineer could choose between only two basic anchor concepts—the deadweight anchor or the drag-type anchor—when designing a mooring system. These anchors are not suited to the demands imposed on them by deep-sea moorings. Deadweight anchors require oversize lines and connective gear and heavy-duty handling equipment because they have a low holding-capacity-to-weight (efficiency) ratio. A concrete weight will moor less than three-tenths of its in-air weight, even less when on dense sand or rock. Large, conventional drag anchors have efficiencies as high as 20:1,* but, usually, efficiencies range from 5:1 to 10:1. The Navy stockless anchor has an efficiency as low as 2:1. To develop these efficiencies, loads must be applied horizontally at the anchor, which is impractical in the deep ocean. In addition, drag anchors can resist loads in only one direction; therefore, when they are used in a stable moor, multiple legs are required. To alleviate individual deficiencies, deadweight and drag-type anchors are often used in tandem in the deep ocean; however, it is probable that the drag anchor does not embed properly because of the restraint imposed by the deadweight.

Many of the deficiencies of deadweight and drag anchors can be overcome by using direct embedment anchors. Therefore, the Naval Civil Engineering Laboratory (NCEL) initiated a program to develop a direct embedment anchor that was practical, efficient, and reliable for mooring surface, subsurface, and seafloor Naval structures in the deep sea and to develop techniques for predicting the holding capacity of these anchors when subjected to a variety of loading conditions.

DIRECT EMBEDMENT ANCHORS

Direct embedment anchors maximize anchoring efficiency and minimize surface operational and handling requirements. The attributes of this type of anchor are due to a major portion of the holding capacity being derived from the shear strength of the soil instead of the mass of the

* The STATO anchor for some seafloor conditions.

anchor. Because they resist vertical as well as horizontal loads, direct embedment anchors do not require long scopes of line. Also, this type of anchor does not require dragging to embed and, therefore, can be accurately positioned on the seafloor.

Direct embedment anchors can be driven by gun, rocket, free fall, or other means. However, when considering the current deep-ocean technology in early 1968, driving an anchor by vibration appeared to be the most promising method of achieving early project goals. The concept of embedding anchors by vibration was derived after piles and coring tools were successfully driven by vibration. Of particular interest, as it applies to deep-water applications, was the obtaining of core samples in 3,000 feet of water off the California coast with a vibracorer (Ocean Science and Engineering, Inc., 1966).

Vibratory driving affords many advantages in achieving a deep-ocean anchorage. Continuous power application allows for accommodation to variable seafloor conditions. The deliberate embedment allows the penetration characteristics to be monitored, if desired, to provide information for evaluating anchor holding capacity. Available electric power supplies (batteries) are relatively inexpensive, can be considered expendable, and do not involve ordnance restrictions. In addition, an efficient, fast-keying fluke developed for the free-fall anchor (Smith, 1966) lends itself to use in the vibratory anchor concept.

There are negative factors. Slow penetration requires that the ship keep station if the line to the anchor cannot be cast free. Penetration into coral or rock is not feasible, but they comprise less than 1% of the seafloor. Also, the very nature of the concept dictates that the anchor be of a long, slender configuration, thereby making it awkward to handle on shipboard and difficult to stabilize on the seafloor during embedment. However, the advantages outweigh these limitations, therefore, the vibratory anchor should find immediate application in deep-sea mooring systems.

PROTOTYPE VIBRATORY ANCHOR

The design and fabrication of a prototype vibratory anchor (Figure 1) were performed under contract by Ocean Science and Engineering, Inc., and was reported by Mardesich and Harmonson (1969). The contractor conducted tests to confirm the overall functionability and integrity of the prototype design in shallow and deep water. Two units were delivered to NCEL in November 1968 wherein a test program was begun to determine the capabilities and limitations of the prototype and to establish criteria for improvements if necessary. The results of the tests with the anchor over

a range of conditions and an analytical study to optimize its holding capacity for a range of seafloor soils were reported by Smith et al. (1970). From these tests and analyses, a second generation vibratory anchor evolved. Improvements were made to the support guidance system, power supply, shaft-fluke assembly, and the vibrator.

SECOND GENERATION VIBRATORY ANCHOR

The second generation vibratory anchor (Figure 2) is a tall metal construction comprised of four elements: a vibrator, a fluke-shaft assembly, a support-guidance frame, and a storage battery power pack. It stands about 18 feet tall, measures at its greatest width 8 feet, and weighs about 1,800 pounds. It is lowered to the seafloor with a single line at about 100 fpm and, on contact, it begins to operate. The vibrator drives the fluke-shaft assembly into the seafloor at a rate dependent on seafloor conditions After about 10 feet of embedment the support-guidance frame is mechanically triggered by the vibrator, opening up to allow the fluke-shaft assembly to pass through. Embedment continues until the driving capacity of the anchor is balanced by the soil resistance or until the batteries are exhausted. When driving ceases, the line to the anchor is pulled, causing the anchor fluke to rotate into its resistive position which completes the operational process of the anchor.

Vibrator

Description. The vibrator unit produces a peak-driving sinusoidal force of 12,500 pounds at a frequency of 75 Hertz. The force is generated by two rotating eccentric weights that are geared together to cancel horizontal forces. Each eccentric is driven directly by a four-hp electric motor. The motors are wired in parallel so that if one motor becomes inoperative the other will continue to drive the vibrator (albeit at a lower frequency and, hence, lower driving force). The eccentrics and the gears attached to them are housed in a pressure-resistant aluminum block. The motors are bolted to this block, and pressure-resistant aluminum cylinders are fitted over the motors.

A steel plate, which is attached to the base of the aluminum block, is used to connect the vibrator to the top of the shaft. A hole bored through the vibrator and the adaptor plate allows passage of a wire rope (anchor wire) to the interior of the pipe shaft.

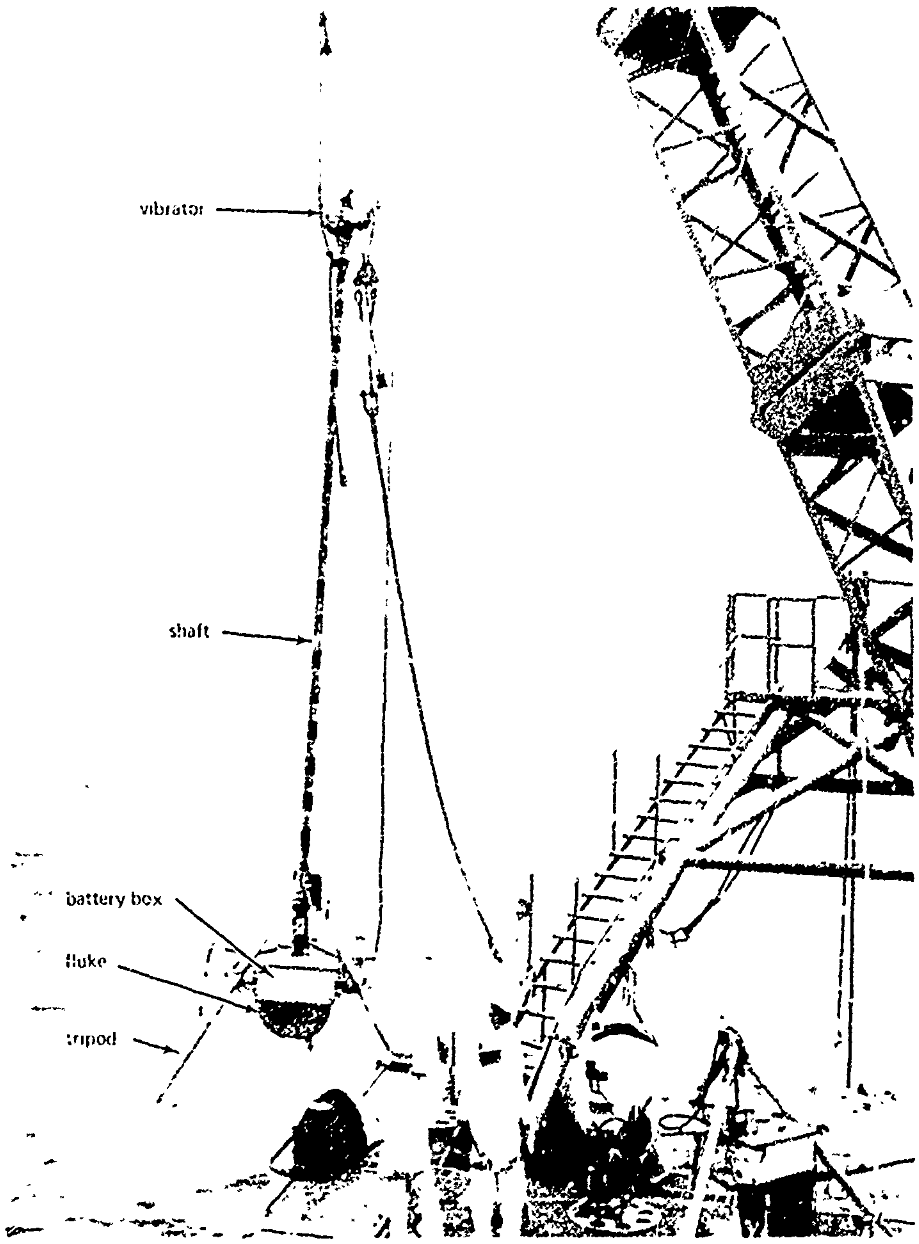

Figure 1. Prototype vibratory anchor.

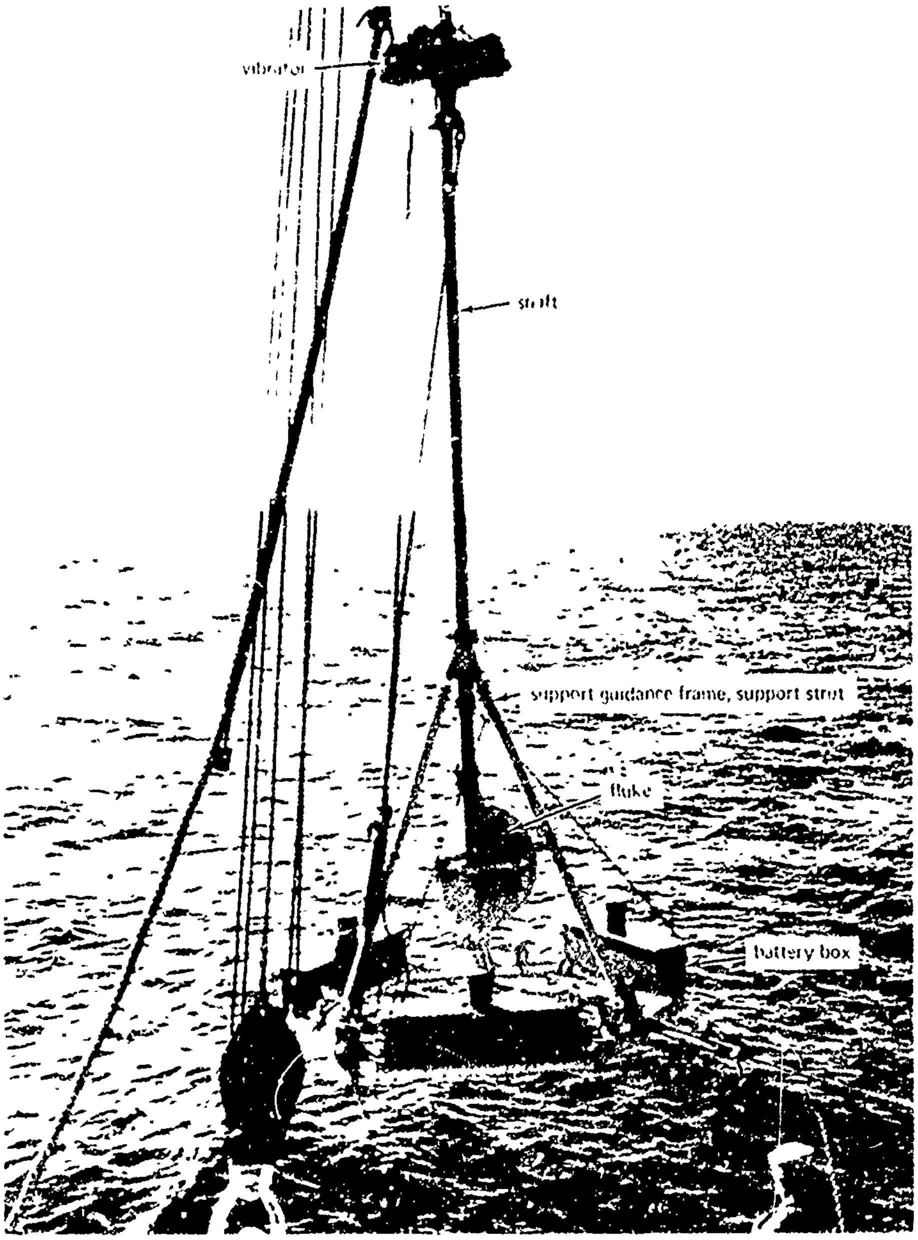

Figure 2. Second generation vibratory anchor.

Prototype Modifications. The driving force of the vibrator was increased about 25%, from 10,000 pounds to 12,500 pounds. This was accomplished by hollowing out the steel eccentrics and filling them with lead; no other structural modifications were required. In the prototype anchor the eccentric gears were lubricated with 1/2 cup of SAE 10 oil. It was found that this oil could work its way to the motors and short them out. The gears are now lubricated with wheel bearing grease. The O-ring seals at the end caps of the motor housings were changed from a corner-type seal to a face-type seal, because the corner-type seal was susceptible to being pinched during assembly. An O-ring seal was provided at the interface of the vibrator body and its cover plate, replacing a Teflon sheet. The Teflon sheet proved ineffective in sealing the vibrator body against water intrusion when the mating surfaces were scratched or marred.

Shaft-Fluke Assembly

Description. The shaft-fluke assembly is composed of a 15-foot-long pipe shaft and a Y-shaped steel plate fluke. The shaft has weldments at its top and bottom for attachment of the vibrator and the fluke, respectively. The fluke is made of steel plate that is cut in two half circles and one quarter circle and then welded together to form a "Y" shape with equal angles. The fluke is structurally linked to the lower end of the shaft with a steel bar (fluke link) that is pinned to the eccentric point of the quarter circle plate. The fluke presents a minimum of resistance to penetration as it enters the soil edgewise, but keys with little vertical displacement to offer a large surface area to resist pullout. A 2-foot-diameter fluke is used in stiff clay and dense sand, a 3 foot-diameter fluke in loose sand and soft clay, and a 4-foot-diameter fluke in very soft clay.

During penetration the fluke is locked securely to the shaft so that all of the vibration energy is transmitted to the fluke and on into the soil. This locking mechanism must be capable of being released after the anchor has been embedded. It consists of two identical lock-releases each having an over-center toggle pinned to the shaft, an adjustable eye bolt attached to the fluke, and a wire strap interconnecting these two parts (Figure 3). The toggles are put over-center, and the nuts on the eye bolts are tightened to clamp the fluke to the shaft. Each toggle has a protrusion that reaches the interior of the pipe shaft through a slot. A tripping slug attached as a termination to the anchor wire that is within the shaft lies below the toggles, and upward movement of the slug pushes the toggles back over center, thereby unlocking the fluke from the shaft. Shear bolts restrain the anchor wire termination from moving up the shaft to the vibrator after the toggles are tripped. If the shaft were to break off because of lateral loading, the anchor wire would still be linked to the lower portion of the shaft, and the anchorage would still be in place.

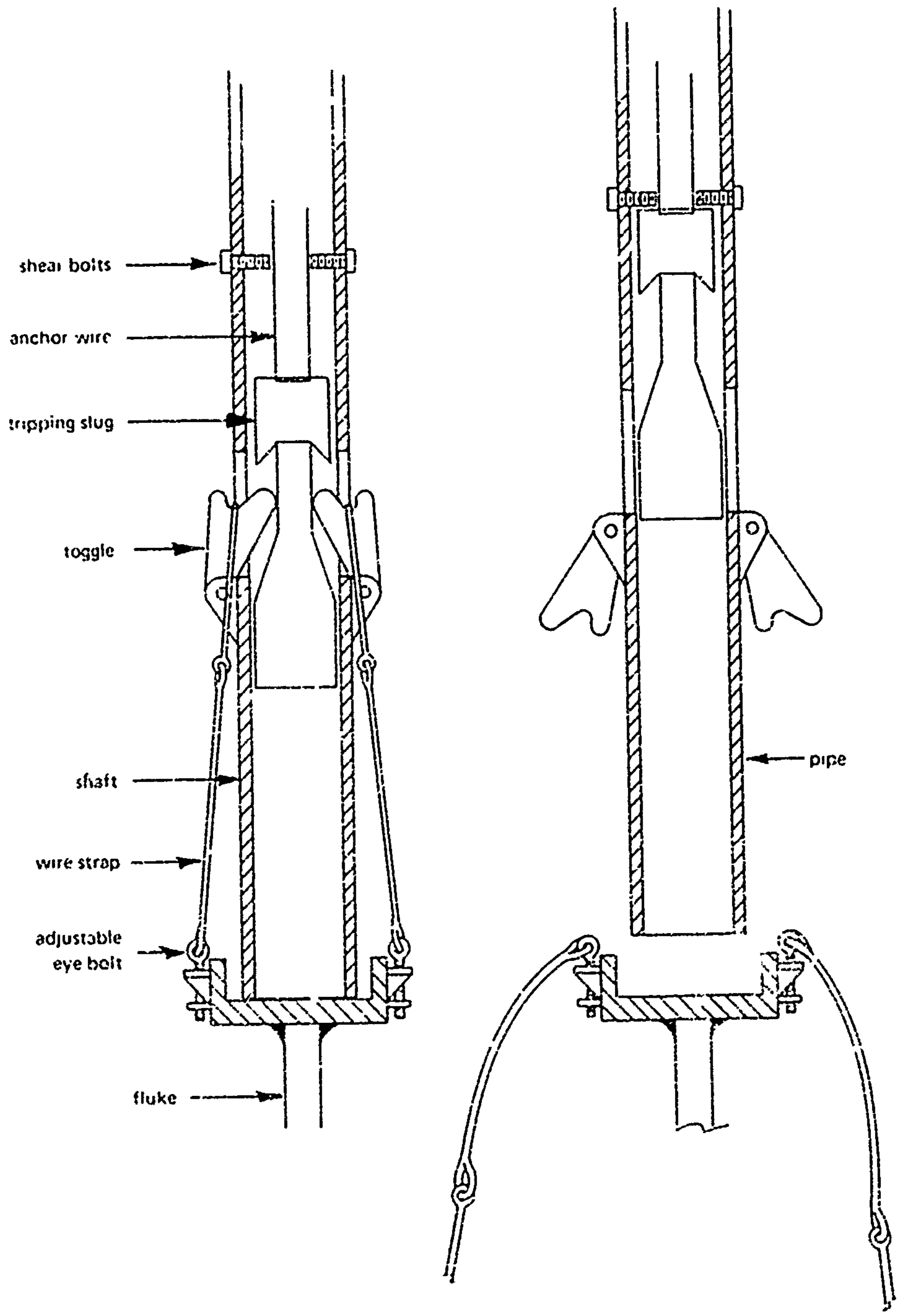

Figure 3. Fluke locking mechanism

Prototype Modifications. Several modifications were made to the shaft-fluke assembly. The shaft was shortened 6 feet. Flukes ranging from 2 to 4 feet in diameter are now used to accommodate varying soil conditions, whereas the prototype anchor used only a 3-foot-diameter fluke. Locking the fluke to the shaft was previously accomplished by closing the toggles over-center with toggle bar tools. If proper tension were not achieved, the connection had to be taken apart, the take-up links adjusted, and the connection remade. Often more than 30 minutes were required to make the connection properly. The connection is now done in about 5 minutes by adjusting nuts on a pair of eyebolts. In the prototype anchor the terminal slug of the anchor wire bore against the vibrator adaptor plate, thereby transmitting load down the shaft to the fluke. Horizontal loads could break the shaft off near the soil surface, and the anchorage would be lost. To prevent this occurrence, shear bolts were placed at the lower end of the shaft to stop upward movement of the slug after the toggles had been tripped over-center. If the shaft should break near the soil surface, the integrity of the anchorage would be maintained.

Support-Guidance Frame

Description. This frame supports and guides the shaft during the first 8 feet of embedment but does not restrict the vibrator from driving the fluke and shaft as deep into the seafloor as possible. A steel pipe hexagon about 7 feet across forms the base of the frame; battery boxes and support struts are attached to alternate sides of the frame. The struts, which are also made of steel pipe, are attached to the frame with a pinned connection that allows them to rotate. At the upper end of each strut, a one-third axial section of a steel tube is attached so that, when all three struts are in position, the tube sections form a guide sleeve for the pipe shaft. The segmented guide sleeve is held together by a clamp that releases by the action of the vibrator and then falls apart. The support struts then rotate out of the way under the influence of gravity (Figure 4). Weldments on the frame allow the struts to fall only in a clockwise direction as viewed from above, and steel bumpers prevent the falling struts from hitting the battery boxes. Elastic cords are provided to assist strut rotation.

Prototype Modifications. The support-guidance frame represents a total change from the prototype tripod. The tripod offered such high resistance to downward movement in water that on several occasions the motors were inadvertently started during lowering. The position of the battery boxes (halfway up the tripod) required heavy lifting during assembly.

The triangular base did not prove sufficient for stabilizing the anchor on the seafloor during the early stages of penetration. Finally, the fixed guide sleeve at the apex of the tripod limited penetration to 6 feet less than the length of the shaft, that is, the shaft had to be 21 feet long to achieve 15 feet of embedment. The new support-guidance frame eliminates all of these problems. Frontal area has been reduced by over one-third, the battery boxes are attached at ground level and require little lifting, the least axis of rotation of overturning has been increased from less than 3 feet to over 3-1/2 feet, and penetration of the shaft into the seafloor is not restricted. The improvements resulted in a lower center of gravity, thereby making the anchor more stable, the height of the anchor has been reduced 6 feet, adding to its stability and also making it easier to handle on shipboard.

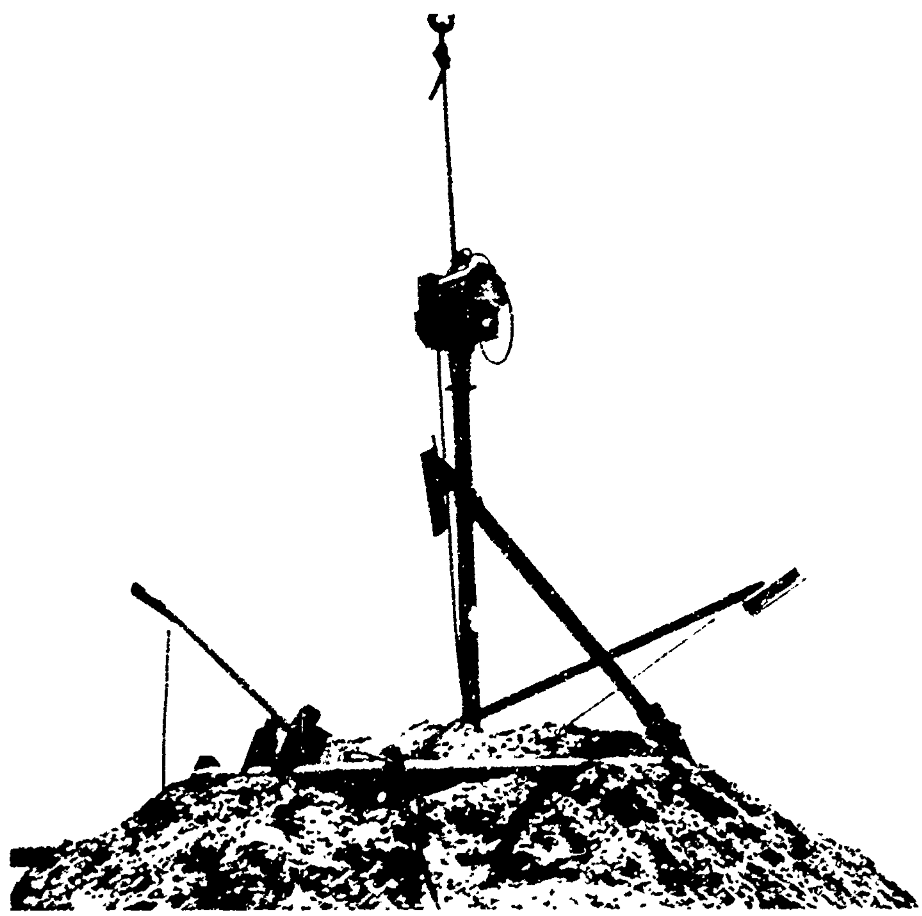

Figure 4. Support guidance frame; anchor embedded about 10 feet in sand on beach.

Power Supply

Description. Power for the vibrator is supplied by 20 lead-acid batteries providing 240-volt, 20-ampere service. Three oil-filled, pressure-compensated steel boxes bolted to the base of the support-guidance frame house the batteries and a motor starter. The batteries are 12-volt, 30-amp/hr garden tractor type batteries wired in series. Each of two boxes contains eight batteries; the third box contains four batteries and the motor starter. The boxes are interconnected with an electrical lead to supply 240 volts for full running power and another lead to provide a 96-volt source for initial motor starting. All electrical penetrations into the battery boxes are plastic bulkhead connectors rated to 20,000 lb/in.^{2} hydrostatic pressure. The circuitry has a floating ground.

The motor starter is activated on touchdown by a spring-loaded release fork. Displacement of the shaft-fluke assembly relative to the support-guidance frame trips the spring and allows the fork to be pulled. For the first 8 seconds, only 96 volts are supplied to the vibrator so that it can build up speed before the full 240 volts are supplied. Switches in the power circuit are solid state and pressure rated to 20,000 feet. Once the vibrator has been activated, it cannot be turned off; it will stop only if an electrical failure occurs or the batteries are discharged.

Prototype Modifications. The motor starting circuit and hardware were changed. In the prototype anchor a spring-driven, mechanically reduced voltage motor starter with seven voltage steps was used. Because mechanically reduced voltage motor starters of the type used in the prototype anchor are no longer commercially available, the starter was changed to a two-step voltage application device utilizing solid state components.

Additional Features

A pinger that continuously operates is provided to determine how close the anchor is to the bottom by acoustic reflection. It is also used in an attitude circuit, turning off when the anchor overturns. Overturning also opens the motor starting circuit. If the anchor should remain overturned for 20 seconds, the starting circuit locks, and the motors cannot be started until the anchor is returned to the surface and the circuit reset. If the anchor is set upright within 20 seconds, the motors will be activated.

There are several rigging features. An elastic cord is attached to the power cable that runs to the vibrator to pull it out of the way as the anchor embeds. A spring-actuated quick release is attached to the vibrator and is held closed by a wire from an arm on the release to the support guidance

frame. The main lowering line is attached to the release through a bridle and fairlead block. On touchdown the release is opened, and about 25 feet of slack anchor wire cable is brought into play as an immediate measure against overturning the anchor.

ANCHOR OPERATION

Once the anchor has been deployed from the floating work platform, it is lowered to the seafloor with a single line at a rate of approximately 100 fpm. Its progress can be monitored with depth sounding equipment. If an active pinger is placed on the anchor, the approach to the seafloor can be accurately monitored by the time difference between the direct signal and the reflected signal.

As the base of the support-guidance frame contacts the seafloor, continued lowering allows the shaft-fluke-vibrator assembly to move downward through the frame. This relative motion releases tension from a 1/8-inch wire rope attached between the quick release and the support-guidance frame, permitting the spring in the quick release to raise the release arm and open the hook. About 25 feet of slack cable comes into play between the end of the lowering line and the anchor, providing protection from overturning due to ship movement or lowering-line catenary. It also allows the shaft-fluke-vibrator assembly to free-fall the remaining distance to the seafloor. The relative movement between the support-guidance frame and the shaft-fluke-vibrator assembly releases a spring that subsequently pulls the motor starter release fork.

Removal of the release fork from the motor starting mechanism lets a spring within the battery box close a magnetic switch. The time from release to closing the switch can be adjusted by changing the orifice of an oil-immersed piston cylinder that is also driven by the spring. Closing the switch activates an SCR which allows 96 volts to be applied to the vibrator's motors. A time-delay relay activates a second SCR 8 seconds later that puts a 240-volt potential across the motors.

Once the vibrator is running, the anchor begins to penetrate into the seafloor with the shaft-fluke-vibrator assembly sliding downward through the guide sleeve at the apex of the support-guidance frame. The rate of penetration is dependent upon sediment conditions and fluke size. After about 8 feet of embedment the vibrator reaches the guide sleeve and triggers the guide sleeve clamp, allowing the support struts to fall out of the way (Figure 4). Further embedment, which is then limited only by the driving ability of the vibrator, will continue until the battery pack is exhausted. Field tests have

shown that the vibrator will operate for periods in excess of 1 hour. Noise given off by the vibrator is audible and can be monitored aboard ship with a hydrophone.

During the embedment phase, line loads cannot be applied to the anchor or it will overturn. It is imperative, therefore, that the work platform be stabilized by mooring or by a positioning system. Even though 25 feet of slack cable are provided immediately after touchdown, more line must be put overboard to ensure against overturning the anchor.

Once the anchor has ceased to vibrate, load is applied to the lowering line. The applied tension terminates in the anchor shaft at the tripping slug attached to the 7/8-inch anchor wire. Tension builds up until a shear pin that restrains the slug from moving up the shaft is sheared. Upward movement of the slug then forces the fluke locking toggles over center, thereby unlocking the fluke from the penetration position. The slug moves up a few more inches until it bears against the shear bolts, thus transferring line tension to the anchor shaft. This tension moves the shaft upward and rotates the fluke about 90 degrees in the soil by pulling eccentrically on the fluke through the fluke link. After the fluke has been rotated, the anchor is ready for mooring service.

TEST PROGRAMS

Prototype Anchor

The test programs conducted by the contractor and NCEL with the prototype vibratory anchor were limited by the availability of work platforms and equipment. Though procedural details differed from test to test, general procedures were similar. The anchor was assembled and readied on deck, lifted over the side with a crane or ship boom and lowered to the seafloor by a winch. Once on the seafloor, the anchor's vibrator was powered by either the battery pack or by a generator on the deck of the work platform. Uplift loads were usually applied with a multiple-part line and measured with an in-line dynamometer. For shallow-water tests the work platforms were held in a two-point moor, but for deep-water tests the work platform either attempted to maintain station or was allowed to drift free.*

* Some ship captains will not maneuver when a line is in the water for fear of entangling the line in the ship's screws.

Second Generation Anchor

The support-guidance frame of the second generation anchor was checked by embedding the shaft of the anchor about 8 feet into sand. The sand at the test site was underlain at the 6-foot level by a dense layer of fill. To achieve sufficient embedment for the test a mound of sand 5 feet high was constructed, and the anchor placed atop it. Power for the vibrator was supplied from a generator.

Tests were conducted from an ARS class salvage vessel at the 6,0' foot depth in the Santa Cruz Basin near geographical coordinates 119°38'W, 33°49'N. This site was chosen because it has a flat bottom and soil data to 10 feet are available from nearby locations. The anchor was lifted over the side of the ship with the main boom and lowered into the water with a whip line until the weight of the anchor was transferred to the lowering line that had been placed over the bow roller. Seventy-two hundred feet of lowering line in three pieces were on the ship's towing drum and was fair-led to the bow roller. It was necessary to lower the anchor from the bow of the ship so that the ship could be maneuvered without fear of entangling the lowering line in the ship's screws.

The anchor was lowered to the seafloor at about 100 fpm; its progress was monitored with a precision depth recorder (PDR). Once the anchor was on the seafloor, the vibrator was monitored with the PDR by listening to the sound it emitted. During the embedment phase, a LORAC navigational system provided data for the bridge so that corrective movements could be made in an attempt to keep the ship on station. A carpenter stopper and a load cell attached between a secure fixture on the ship and the lowering line were used to measure load applied to the anchor. The ship backed down to apply test loads, and a continuous trace of the load was made. After the anchor pull test was completed, the anchor was returned to the ocean surface and placed on board.

After the anchor was tested in 6,000 feet of water, it was also deployed in shallow water (100 feet) in order to monitor the overall performance of the anchor, especially its newly modified systems.

TEST RESULTS

Prototype Anchor

The results of tests by the contractor and NCEL with the prototype anchor are summarized in Table 1 as Operations I through IX. In general, the anchor achieved good resistance to short-term uplift loads even when only

moderate penetration was attained. When adequate penetration was not achieved, it was usually attributable to an electrical or mechanical failure or an operational difficulty, not to an inability to achieve sufficient penetration. Of particular note is Operation III, where the contractor successfully tested the anchor in 2,460 feet of water with 7-knot winds and a sea state of 1. Prior to that test four unsuccessful attempts with less favorable conditions were made by the contractor.*

Second Generation Anchor

The beach tests show that the support-guidance frame and the clamping collar at the split guide sleeve function as designed. The action of the vibrator triggered the release of the clamping collar, and the support struts rotated out of the way, giving the vibrator an unobstructed path to further embedment. A vibrator with increased driving force was operated for about an hour; an inspection of the vibratory unit revealed that no damage occurred.

Tests at sea with the second generation anchor are summarized in Table 1 as are Operations X through XII.

The first test at 6,000 feet from the salvage vessel was a partial success. Deployment and recovery of the anchor was completed without difficulty. However, functional testing was not accomplished, because the anchor did not activate upon reaching the seafloor. Deployment and recovery was accomplished smoothly in very good sea conditions—light winds, 2- to 3-foot swells, and a 6-inch chop. The motors failed to start because a wire line that is used to pull the starting fork broke before the fork was pulled. The wire line has a breaking strength of about 150 pounds, and only about a 5-pound force is required to pull the fork. The actual cause of the break was never determined. However, a different method of pulling the fork was devised. With this method, the parting of the pull wire would start the motors as does relative movement between the shaft and the support-guidance frame.

The second test at 6,000 feet was also conducted from an ARS salvage vessel. Sea conditions were not favorable—12- to 16-knot winds, 4- to 6-foot swells, and a 1-foot chop existed. Deployment and recovery of the anchor was again accomplished without difficulty. The smoothness of lowering the anchor was improved over the first cruise by providing a larger sheave at the point of line travel reversal in order to pass the fittings connecting the separate lengths of wire. On the first cruise it was necessary to stopper the line off and work each set of fittings through the sheave, this resulted in a loss of time and a break in continuity.

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* These tests are not presented in Table 1, because some were aborted when the anchor entered the water.

Table 1. Summary of Vibratory Anchor Tests

Operation	Date	Anchor Configuration	Water Depth (ft)	Soil Type	Penetration (ft)	Maximum Measured Load (kips)	Comments
I	Jul 1968	prototype	33	harbor soil	16	NA	Flukes welded closed, 9 minutes of vibration.
			33	harbor soil	12	62	25 minutes of vibration.
II	Aug 1968	prototype	unknown	sand	16	NA	16 feet of penetration in 2 minutes.
III	Nov 1968	prototype	2,460	unknown	unknown	52	Anchor assembly functioned satisfactorily, fluke did not open.
IV	Mar 1969	prototype	1,000	unknown	none	--	Motor did not activate.
			1,000	unknown	none	--	Motors activated, but ship motion prevented embedment of anchor.
V	May 1969	prototype	40	sand	none	–	Operations were conducted with support of Naval Underwater Center. Attempt to embed anchor was unsuccessful due to fluke linkage problem and electrical cable failure.
VI	May 1969	prototype	500	clay	15	5	All anchor components functioned satisfactorily; soil extremely weak.
VII	Aug/Sep 1969	prototype	55	sandy silt	4-½	14	Faulty load measurement.
			43	sandy silt	4-½	40	Linkage between fluke and shaft broke.
			43	sandy silt	2	18	Linkage between fluke and shaft broke.
			43	sandy silt	7	62	Linkage failed; fluke lost.
			52	sandy silt	6	70	Relatively high holding capacity with small penetration.
			52	sandy silt	5	57	Relatively high holding capacity with small penetration.
VIII	Mar 1970	prototype	95	clay-silt	9-½	60	Penetration limited by stiff soil.
			95	clay-silt	5-½	9	Vibrator failed, fluke did not open.
			95	clay-silt	9-½	50	Penetration limited by stiff soil.
			95	clay-silt	4	12	Vibrator failed.
IX	Jun 1970	prototype	600	clay-silt	5	16	Vibrator ran for over 1 hour.
X	Nov 1971	second generation	6,000	clay	none	–	Motors did not activate.
XI	Jun 1972	second generation	6,000	clay	none	-	Motors activated, but ship motion prevented embedment.
XII	Dec 1972	second generation	100	sandy silt	9-½	62	Tested from moored work platform.

During lowering, the ship managed to maintain position within tolerable limits. However, as sea conditions grew worse, the ship was blown off its heading, requiring it to make a full turn. After the anchor was on the seafloor, the ship was not able to maintain position within the required distances. Consequently, the anchor overturned and was dragged on the seafloor, preventing successful embedment of it.

A load cell was rigged to the lowering line, and a test load was applied by backing the ship down. No load was measured, and the anchor was recovered. When the anchor was brought onboard the vibrator was operating.

The shallow water test was conducted in 100 feet of water from a moored barge with the anchor in its full operational mode. The anchor was placed over the side with a crane and lowered to the seafloor. It activated on touchdown and vibrated for about an hour. Divers reported that the anchor embedded 9 feet. The support-guidance frame triggered, and the struts moved out of the way of the vibrator. During the breakout test, over 40,000 pounds pull was maintained for 11 minutes; the ultimate pullout force was 62,000 pounds.

DISCUSSION

Tests with the prototype vibratory anchor showed that when the anchor functioned properly the test pull holding capacity usually fell between 40,000 and 70,000 pounds. However, in most cases, the measured loads do not indicate the true short-term holding capacity of the anchor because of the presence of a suction force. This suction force dissipates with time. Therefore, to have a more reliable estimate of the anchor's holding capacity, the test values must be reduced when suction is present (Taylor and Lee, 1972). The nominal correction is about 50% in clay, but it varies with soil shear strength and relative embedment depth of the fluke. In coarse sand there is no suction, except when the anchor is loaded very rapidly. For other soils the nominal correction probably lies somewhere between 0 and 50%. For the tests in the harbor soil and a clayey-silt a correction factor of about 50% should be applied. This gives short-term holding capacities from 25,000 to 35,000 pounds. (The procedure in the Appendix for estimating short-term holding capacity in clay gives values that agree favorably with these results.) Taylor and Lee do not recommend reduction factors for soils other than clay. Therefore, for the tests in sandy-silt it would appear conservative to apply their maximum suction factor, 7 A c, where A is the projected area of the anchor fluke and c is the soil cohesion. An undrained

shear strength of about 4 psi can be inferred from the maximum driving ability of the anchor and from the fact that the flukes were driven to refusal in the sandy-silt in the final three tests. This value of undrained shear strength indicates that the test pull data in the sandy-silt should be reduced by about 25,000 pounds, giving short-term holding capacities between about 25,000 and 45,000 pounds. If it is assumed that this sandy-silt behaves in a totally cohesive manner, which is unlikely, the short-term holding capacity using a cohesion value of 4 psi calculates to be about 12,000 pounds for the three tests being analyzed. If the soil is assumed to be frictional in nature with a buoyant weight of 50 lb/ft^3 and a friction angle of 35 degrees, the short-term holding capacity figures out to be about 7,500 pounds. Neither of these values compares favorably with the short-term holding capacities estimated from the test results. It would appear that the method presented in the Appendix for calculating short-term holding capacity (Taylor and Lee, 1972) is conservative, perhaps by more than a factor of 2, for predicting the short-term holding capacity of shallowly embedded anchors in sandy soils.

With the soil data from Operations VII, VIII, and IX, an evaluation procedure in the Appendix for calculating embedment depth can be made. However, an evaluation can only be made for tests in which the anchor was driven to refusal, such as Tests 4, 5, and 6 of Operation VII, Tests 1 and 3 of Operation VIII, and the single test of Operation IX. For Operation VII calculated penetration depths for Tests 4 and 5 are about 6-1/2 feet and for Test 6, about 6 feet. These results compare favorably with the test penetrations of 7, 6, and 5 feet, respectively. The calculations were made assuming a friction angle of 35 degrees and a buoyant unit soil weight of 50 lb/ft^3. The calculated penetration for Operation VIII is 9 feet using soil data presented by Demars and Taylor (1971). The test penetrations of 9-1/2 feet for both Tests 1 and 3 are in good agreement with the predicted value. For Operation IX, based on soil data from Demars and Taylor, the penetration depth figures out to be about 5-1/2 feet; the actual penetration at this site was measured to be between 4 and 6 feet. Based on these limited tests it would appear that the method given in the Appendix for estimating penetration gives fairly accurate results when the soil properties are known.

The modifications to the prototype design (see below) appear to have made the anchor easier to assemble, easier to deploy, more reliable, and more capable of operating in a wide range of seafloor soils. The most significant change was to the support-guidance frame. The ability of the frame to pass the shaft-fluke assembly without restriction has eased both assembly and deployment. Heavy lifting of the power pack has been eliminated, because the batteries boxes are now carried at the base of the frame.

The power pack and frame do not have to be assembled and disassembled when the shaft-fluke assembly is put in or taken out of the frame. This saves considerable time in assembling the anchor. In addition, because the shaft-fluke assembly passes through the frame, it was possible to shorten the shaft by 6 feet and still maintain 15 feet of embedment.

The fluke-locking device has remained basically the same; only the method of adjusting it was changed. It is now only necessary to tighten two nuts with a wrench. The improved fluke-locking device has reduced the time required to secure the fluke to the shaft from a minimum of 30 minutes to 5 minutes. The starter system of the power pack was changed from a mechanical system to solid state circuitry. This allows for more precise control over the starting characteristics of the vibrator and eliminates the arcing and burning that was associated with the previous starter. The battery arrangement was changed to make it easier to assemble and charge the power pack. A range of fluke sizes is now available for the anchor. Methods for selecting the appropriate fluke for specific conditions are presented in the Appendix; however, adequate field verification is lacking. Providing a range of fluke sizes has made the anchor adaptable to a wider range of soils than the prototype anchor was effective in.

Failure of the motors to start on the first operation at 6,000 feet exemplified the problems associated with deep-ocean work. Even though it was possible to determine what mechanical system failed, it was not possible to determine why it failed. With a work system designed to be expendable, sophisticated monitoring systems cannot be provided. Consequently, when a detrimental failure occurs, it often cannot be determined when it occurred or what caused it. Inspection after the event usually leads to speculation that cannot be substantiated except in the most straightforward cases. In this case, it was possible to devise a mechanism that circumvents a similar failure. The new motor starter release has been bench tested and appears to be very reliable. During the second operation in 6,000 feet of water and in the shallow-water test it performed satisfactorily.

It appears that it is not possible to use the vibratory anchor from unstabilized work platforms (not moored or positioned by thrusters) unless sea conditions are ideal, that is, sea state 1 or less. Because it is not practical to rely on having such good sea conditions, it appears the vibratory anchor will be limited to use from moored work platforms (as was accomplished with the prototype anchor) or work platforms that have accurate position-keeping systems.

CONCLUSIONS

1. The modifications made to the prototype vibratory anchor have increased its versatility, improved its operational reliability, and eased its handling aboard a ship at sea.

2. The vibratory anchor is capable of providing from 25,000 to 40,000 pounds of short-term holding capacity in seafloor soils ranging from sands to clay-silts.

3. The procedure presented in the Appendix for predicting short-term holding capacity in cohesive sediments (Taylor and Lee, 1972) appears to give reasonable values based on pull test results in a clayey-silt.

4. The procedure presented in the Appendix for predicting short-term holding capacity in a sandy soil (Taylor and Lee, 1972) appears to give values conservative by at least a factor of 2 based on pull test results of shallowly embedded anchors in a sandy-silt.

5. The procedure presented in the Appendix for estimating the embedment depth of the vibratory anchor appears to give reliable values based on the field test results.

6. The vibratory anchor can and has been used successfully from anchored work platforms to a water depth of 600 feet.

7. The vibratory anchor appears to be functional to its maximum design depth of 6,000 feet, but successful deployment at water depths greater than those a ship can moor in requires a station-keeping ability greater than that of salvage class ships, and probably on the order of dynamic positioning for most sea conditions.

8. Based on the successful test from an unanchored work platform in about 2,500 feet of water it appears that the vibratory anchor can be deployed from anchored work platforms to at least that water depth.

RECOMMENDATIONS

1. Since the vibratory anchor is operational, it should be used in the field to moor equipment in order to gain operational experience.

2. Based on operation experience, use of the vibratory anchor should presently be limited to deployment from anchored or dynamically positioned work platforms.

3. Proof loads should be applied to all vibratory anchor installations to ensure an ability to resist expected in-service loadings.

Appendix

ANCHORAGE DESIGN

The proper use of the vibratory anchor is dependent upon selecting an appropriate size of fluke for the soil conditions encountered. If the soil type and its strength profile are known or if reasonable estimates can be made, it is possible to theoretically design the anchorage through an iterative procedure. First, the depth a given diameter fluke can be driven into the soil is estimated. Second, a distance equal to one fluke diameter is subtracted from the driven depth to account for fluke keying. Third, the holding capacity of the anchor is estimated using the reduced depth. In general, the anchorage is optimized when the fluke is embedded 10 to 20 feet and the holding capacity is between 30 and 40 kips. Therefore, (1) if the penetration is over 20 feet and the capacity is not adequate, another series of calculations with a larger fluke is performed; (2) if the penetration is less than 10 feet and the holding capacity is not adequate, another series of calculations with a smaller fluke is performed; and (3) if the penetration is less than 10 feet and the holding capacity is adequate but erosion is a problem, a smaller fluke should be considered.

Penetration is estimated by equating the vibratory anchor peak driving force plus the weight of the vibrator, shaft, and fluke (bias weight) to the static resistance the soil applies to the shaft-fluke assembly (Schmid, 1969).

For clay the equation is

$$Q + \text{Bias} = A_{fs}c + A_{ff}N_c c + a_s c_r D \qquad (1)$$

where Q = peak vibrator driving force, 12,500 lb

Bias = weight of fluke-shaft vibrator system (lb)

A_{fs} = fluke side area (ft^2)

A_{ff} = fluke frontal area (ft^2)

c = soil cohesion (psf)

N_c = deep bearing capacity factor for clay, 9

a_s = shaft unit area, 0.813 ft^2/ft

c_r = remolded soil cohesion (psf)

D = embedment depth (ft)

The values for Q and a_s apply to the vibratory anchor as developed by NCEL. Terzaghi and Peck (1967) have recommended $N_c = 9$ for the bearing capacity factor for deep foundations. Values of A_{fs} and A_{ff} are given in Table 2. For clays that have a uniform cohesion profile with depth, the above equation can be solved directly for the embedment depth. When the cohesion profile varies as a complex function of depth, it is necessary to solve the equation by trial and error because a particular cohesion value implies a particular depth. However, for seafloor soils the cohesion profile is often specified by a constant function of depth in the form of a ratio of cohesion to effective overburden pressure. Multiplying this ratio by depth and buoyant soil density gives the cohesion at that depth. (The remolded cohesion is attained by dividing the cohesion by the soil sensitivity.) When this is the case, Equation 1 becomes

$$Q + \text{Bias} = A_{fs} \frac{c}{\bar{p}} \gamma_b D + A_{ff} N_c \frac{c}{\bar{p}} \gamma_b D + a_s \frac{1}{S_t} \left(\frac{c}{\bar{p}}\right) \gamma_b \frac{D^2}{2} \quad (2)$$

This equation can be solved for depth in terms of the other parameters using the quadratic equation. The result is:

$$D = \frac{-(X + Y) \pm [(X + Y)^2 + 4W(Q + \text{Bias})]^{1/2}}{2W} \quad (3)$$

where $X = A_{fs} (c/\bar{p}) \gamma_b$

$Y = A_{ff} N_c (c/\bar{p}) \gamma_b$

$W = a_s (1/S_t) (c/\bar{p}) (\gamma_b/2)$

$c/\bar{p}$ = ratio of cohesion to effective overburden pressure

γ_b = buoyant unit weight of soil (pcf)

S_t = soil sensitivity

For sand, Equation 1 becomes:

$$Q + \text{Bias} = A_{fs} \bar{\sigma}_v K \tan\phi_s + A_{ff} N_q \bar{\sigma}_v + a_s \bar{\sigma}_v K \tan\phi_s \frac{D}{2} \quad (4)$$

where $\bar{\sigma}_v$ = effective vertical pressure (psf)

K = ratio of principal soil stresses

ϕ_s = friction angle between steel and sand

N_q = deep bearing capacity factor for sand

Table 2. Computational Values

Size of Fluke Diameter, D (ft)	Fluke Side Area, A_{fs} (ft^2)	Fluke Frontal Area, A_{ff} (ft^2)	Fluke Projected Area, A (ft^2)	Bias Weight[a] (lb)
2	8.3	0.37	2.7	440
2.5	12.9	0.43	4.2	490
3	18.4	0.50	6.1	540
3.5	24.8	0.57	8.3	600
4	32.5	0.67	10.8	680

[a] Shaft, vibrator, and fluke.

The value for N_q is difficult to select. Schmid (1969) illustrated the large divergence of theoretical N_q values for bearing resistance of a strip foundation (the basic frontal shape of the anchor fluke is a thin plate). He noted that, if the higher values were correct, it would be practically impossible to drive objects into sand at large depths. This, however, is done quite frequently. It is recommended, therefore that N_q values for frontal penetration resistance in sand be chosen according to the Prandtl (1921) curve in Figure 5.

Values of K as explained by Smith et al. (1970) are taken as 1.5 for dense sand and 1.0 for loose sand. The angle of friction between sand and steel is independent of soil density and is taken as 26 degrees (Lambe and Whitman, 1969). When the density of the sand varies significantly with depth, Equation 4 must be solved by trial and error. If the sand has a uniform density over the depth of interest or if it can be approximated as such, Equation 4 can be rewritten by substituting the product of soil depth and soil buoyant density for the effective vertical pressure. Equation 4 then becomes:

$$Q + \text{Bias} = A_{fs}\gamma_b D K \tan\phi_s + A_{ff} N_q \gamma_b D + a_s \gamma_b D K \tan\phi_s \frac{D}{2} \quad (5)$$

This equation can be solved for depth in terms of the other parameters using the quadratic equation. The result is:

$$D = \frac{-(I + L) \pm [(I + L)^2 + 4J(Q + \text{Bias})]^{1/2}}{2J} \quad (6)$$

where $I = A_{ff} N_q \gamma_b$

$L = A_{fs} \gamma_b K \tan\phi_s$

$J = (1/2) a_s \gamma_b K \tan\phi_s$

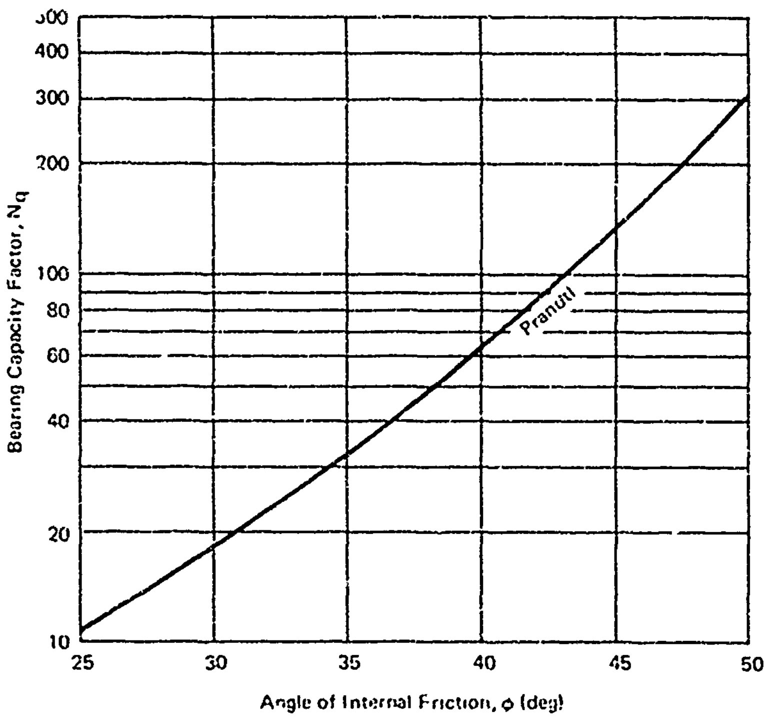

Figure 5. Theoretical bearing capacity factor, N_q, versus angle of internal friction, ϕ, for a strip foundation.

The holding capacity under short-term loading is estimated with the following relationship (Vesic, 1969):

$$F_t = A(c\bar{N}_c + \gamma_b D \bar{N}_q) \tag{7}$$

where F_t = anchor holding capacity (lb)

A = fluke projected area (ft^2)

c = cohesion (psf)

γ_b = soil buoyant weight (pcf)

D = burial depth (ft)

$\bar{N}_c$ = holding capacity factor for cohesive soil

$\bar{N}_q$ holding capacity factor for cohesionless soil

Values of A are listed in Table 2. The burial depth is taken as the driven depth at the fluke centerline minus one fluke diameter. This is conservative, as the fluke keys in less distance than a full fluke diameter. Values of $\bar{N}_c$ and

$\bar{N}_q$ have been given by Taylor and Lee (1972) in the form of graphs (Figures 6 and 7). The holding capacity determined from Equation 7 is commonly termed the short-term static holding capacity. Depending upon soil type and loading conditions this equation may or may not be indicative of the holding capacity available in a particular anchorage. A discussion of the influence of loading conditions and soil type and the methods for accounting for them is presented by Taylor and Lee (1972).

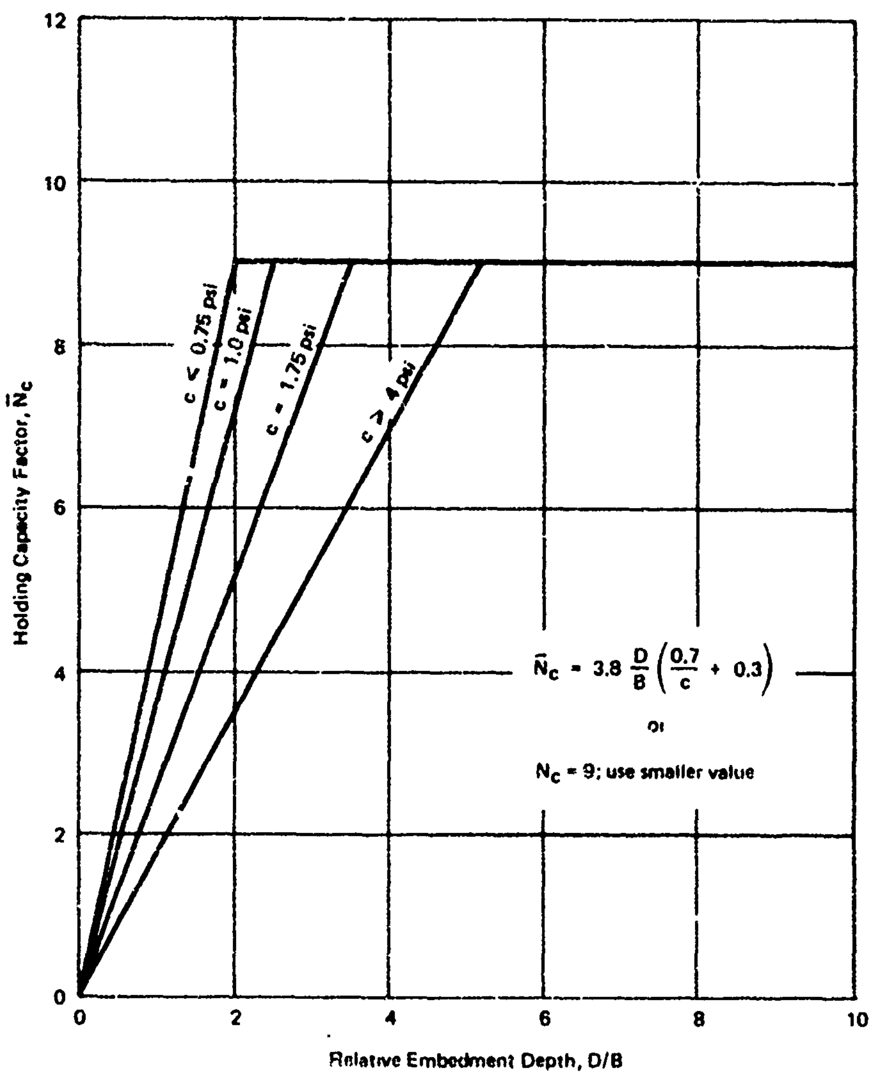

Figure 6. Holding capacity factor, $\bar{N}_c$, versus relative embedment depth for different cohesion values, c.

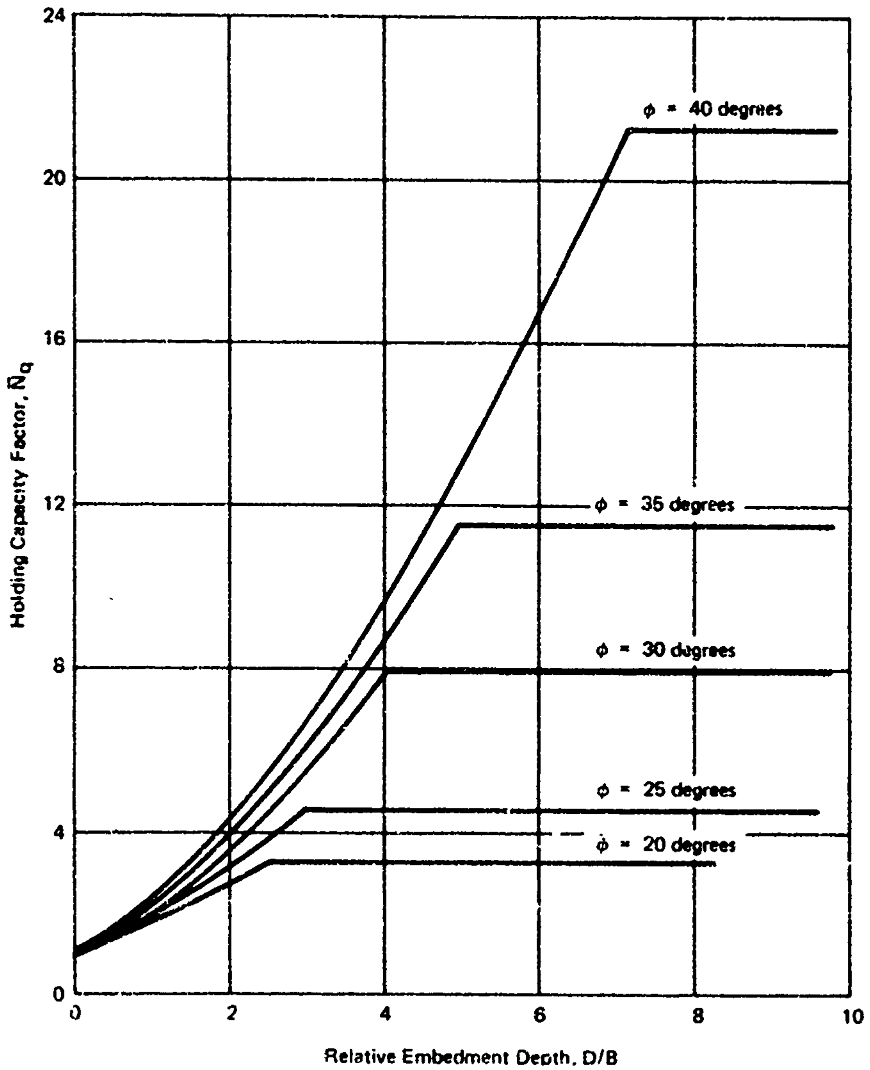

Figure 7. Holding capacity factor, $\bar{N}_q$, versus relative embedment depth in cohesionless soil for different internal angles of friction, ϕ.

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LIST OF SYMBOLS

A	Fluke projected area
A_{ff}	Fluke frontal area
A_{fs}	Fluke side area
a_s	Shaft unit area
B	Fluke diameter
Bias	Bias weight (weight of vibrator, shaft and fluke)
c	Soil cohesion
c_r	Remolded soil cohesion
$c/\bar{p}$	Ratio of cohesion to effective overburden pressure
D	Embedment depth
F_t	Anchor holding capacity
K	Ratio of principal soil stresses
N_c	Deep bearing capacity factor for clay
$\bar{N}_c$	Holding capacity factor for cohesive soil
N_q	Deep bearing capacity factor for sand
$\bar{N}_q$	Holding capacity factor for cohesionless soil
Q	Peak vibrator driving force
S_t	Soil sensitivity
γ_b	Buoyant unit weight of soil
$\bar{\sigma}_v$	Effective unit vertical pressure
ϕ	Friction angle of soil
ϕ_s	Friction angle between steel and sand